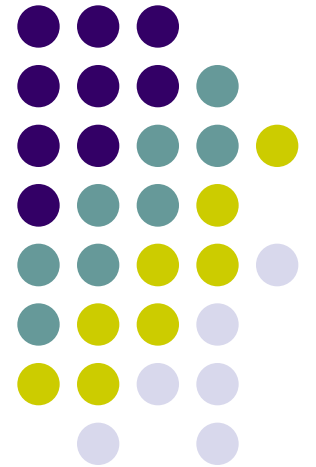
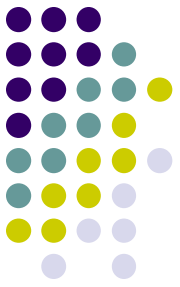


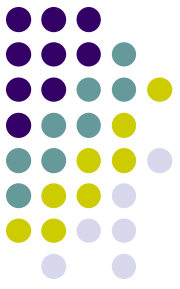
Copernican Revolution



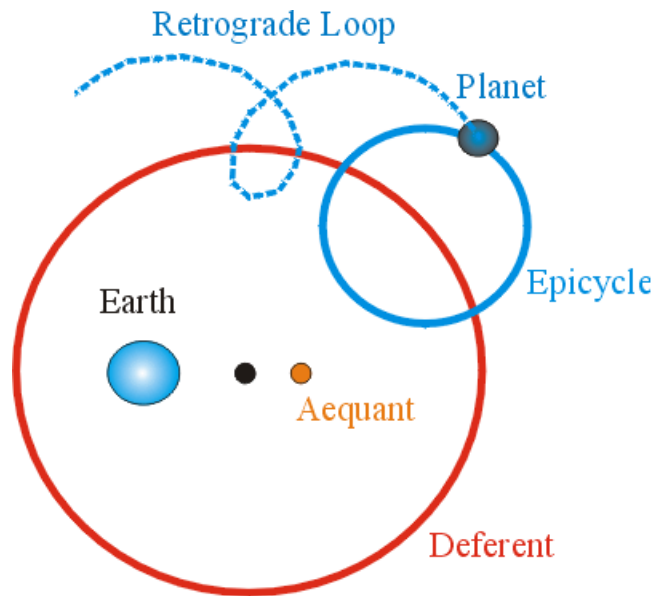
Ptolemy (100-170 AD)



- He completely reworked the Aristotelian world system. By his time astronomical observations improved so much that it became clear that the original Aristotelian system does not agree with them.

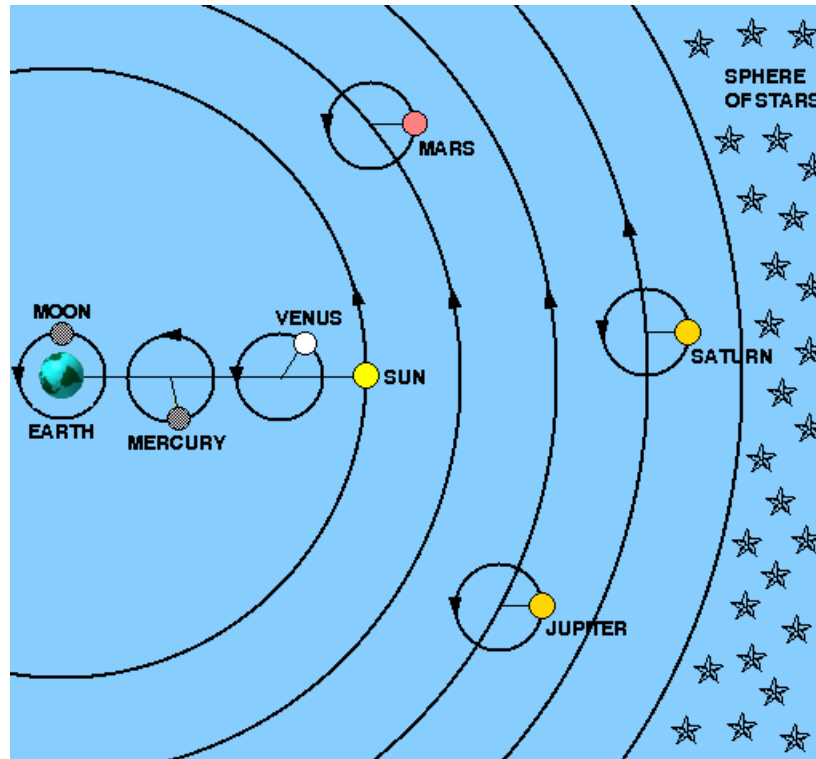
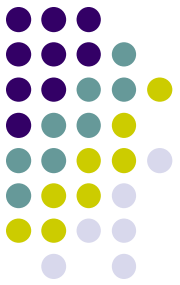


Ptolemaic model



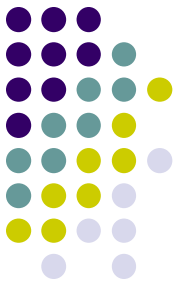
- There is just 1 main sphere per planet: a **deferent**. A planet goes around a small circle called **epicycle**; the epicycle, in turn, goes around the deferent.
- The motion of the epicycle around the deferent is uniform around an off-center point, an **(a)equant**.

Geocentric model of the universe



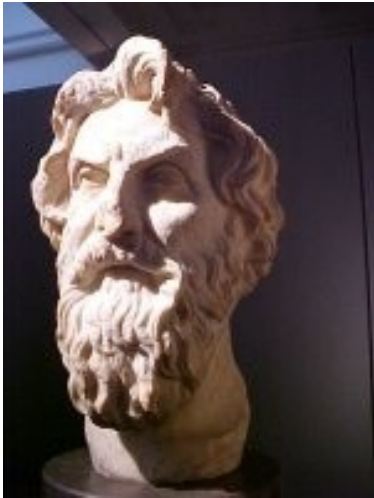
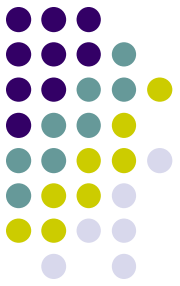
Note: Sun always shines on Venus from behind

Ptolemaic model



- The Ptolemaic model was successful in that it was used to calculate the positions of planets for 15 centuries.
- A common legend claims that more epicycles were added later to Ptolemaic system – this is not actually supported by historians.
- Some Arabic astronomers (“rebels”) did indeed construct model with many epicycles, but with concentric deferents.
- The phrase “adding more epicycles” is often used to mean improving a wrong and unfixable model.

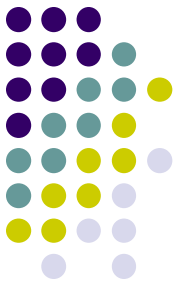
Aristarchus (310-230 BC)



As astronomer, he was well ahead of his time.

By comparing the shadow of the Earth with the angular size of the Moon during a total lunar eclipse, he was able to measure: the size of the Moon

$$R_{\oplus} \approx 3 \times R_{\text{m}} \quad (\text{truth: } 3.67) ,$$



He also measured the Moon-Earth distance:

$$D_{\text{m}-\oplus} \approx 60 \times R_{\oplus}. \quad (\text{truth: } 60.35)$$

(Not bad at all!!!) and the Sun-Earth distance:

$$D_{\odot-\oplus} \approx 20 \times D_{\text{m}-\oplus}. \quad (\text{truth: } 389)$$

(Oops, here he missed a lot!)

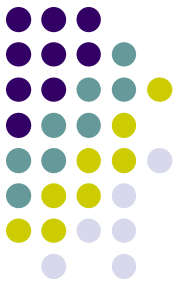


Nevertheless, since the Moon is only 3 times smaller than the Earth, but the Sun and the Moon have the same size on the sky, Aristarchus concluded that the Sun was 7 times larger than the Earth.

He, therefore, proposed the first *heliocentric* model.

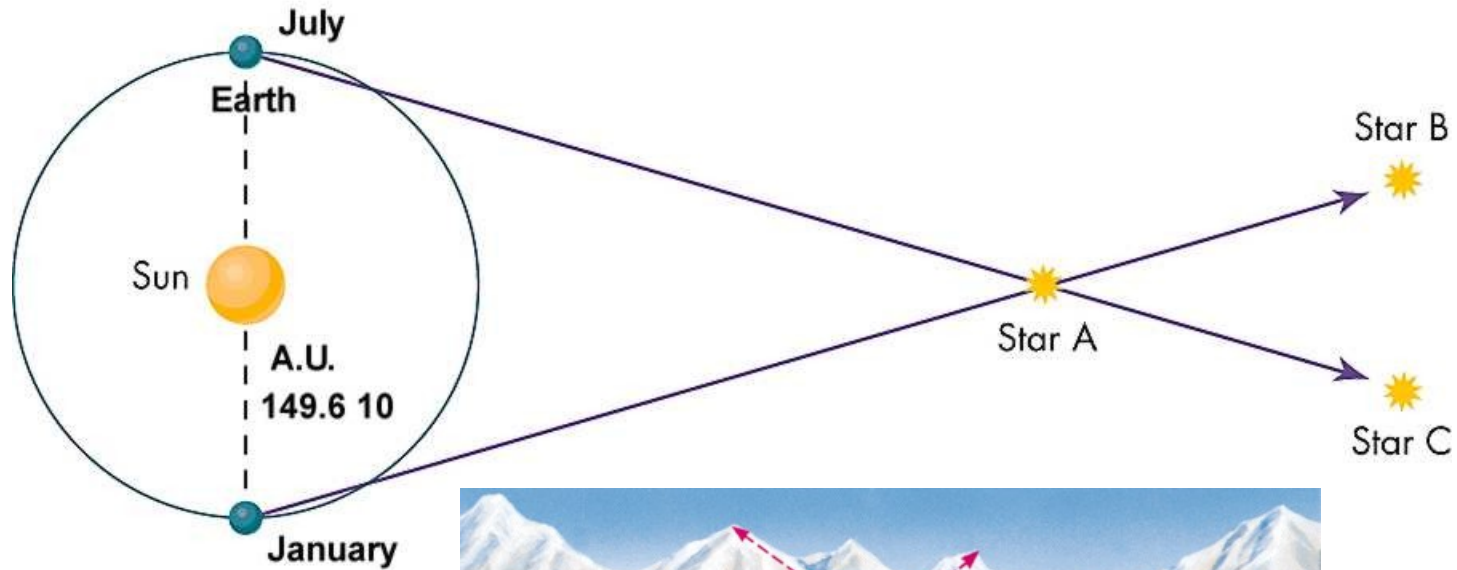
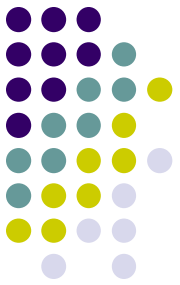
He also proposed that Earth was rotating around its axis.

His model was not accepted because:



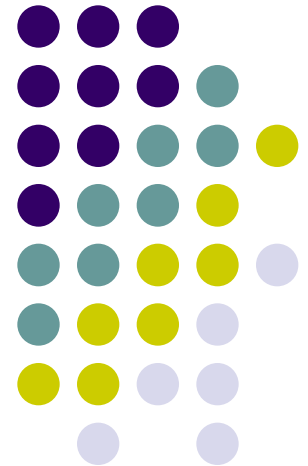
- the Earth was not the center of the universe.
- the Earth then had to move, contrary to observations.
- there should be **stellar parallax** (i.e. apparent positions of stars on the sky should change as the Earth moves around).

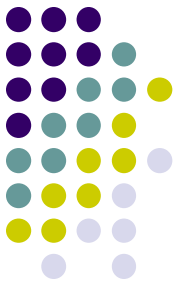
Stellar Parallax



Question:

Why was the parallax not observed?

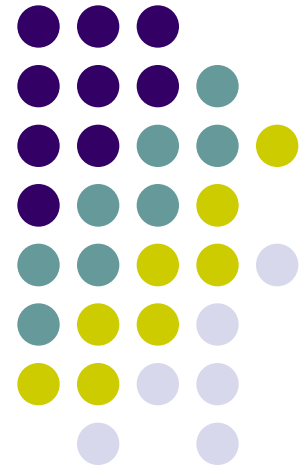


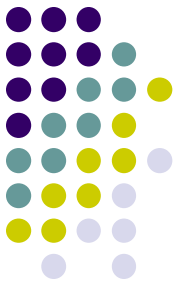


- **A:** the Earth does not move;
- **B:** stars move in unison with the Earth;
- **C:** the parallax exists, but it is so small (because the stars are so far away), that it can only be observed with a good telescope;
- **D:** Einstein discovered that space was curved – in curved space light does not go along straight lines.

Fast Forward 1000 Years

1100 AD





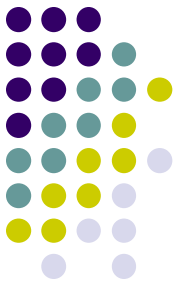
Early Universities

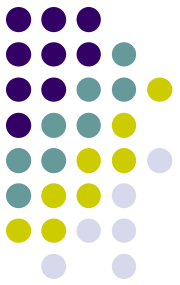
- University of Bologna 1088
- University of Paris 1160
- University of Oxford 1167
- University of Cambridge 1209
- University of Palencia 1212
- University of Salamanca 1218
- University of Padua 1222
- University of Toulouse 1229



...lucens. de.
...solima duxit.

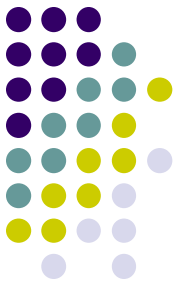
The Discovery of the Earth





Portuguese voyages

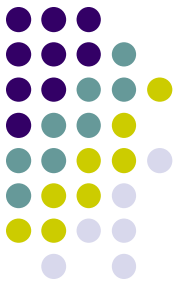
- 1427: Azores (2,000 km)
- 1458: Gambia river (6,000 km)
- 1472: Niger river (12,000 km)
- 1482: Congo river (16,000 km)
- 1488: Cape of Good Hope (22,000 km)
- 1492: America (13,000 km over open water)
- 1497: India (38,000 km)
- 1522: Around the globe (70,000 km)



Revival of Astronomy

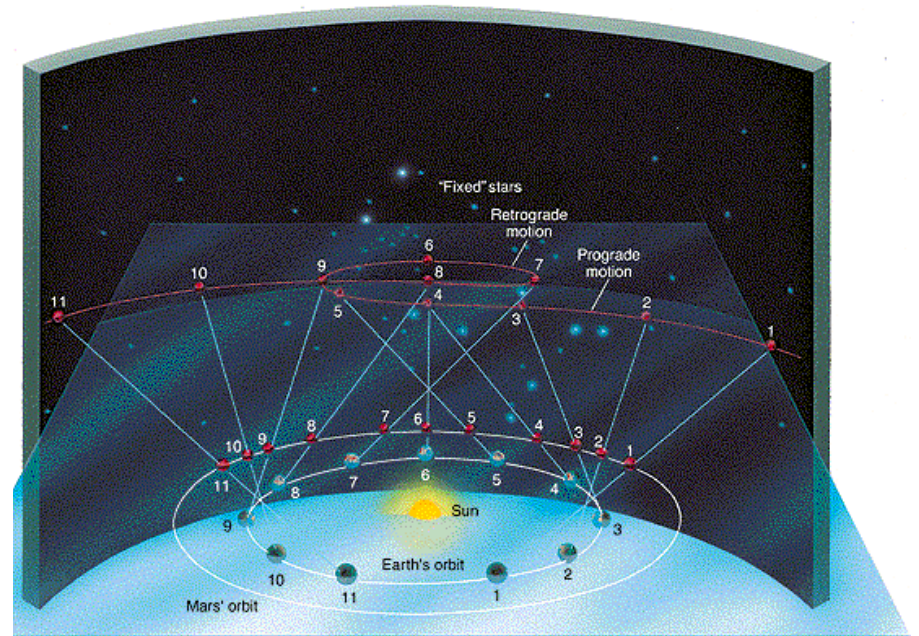
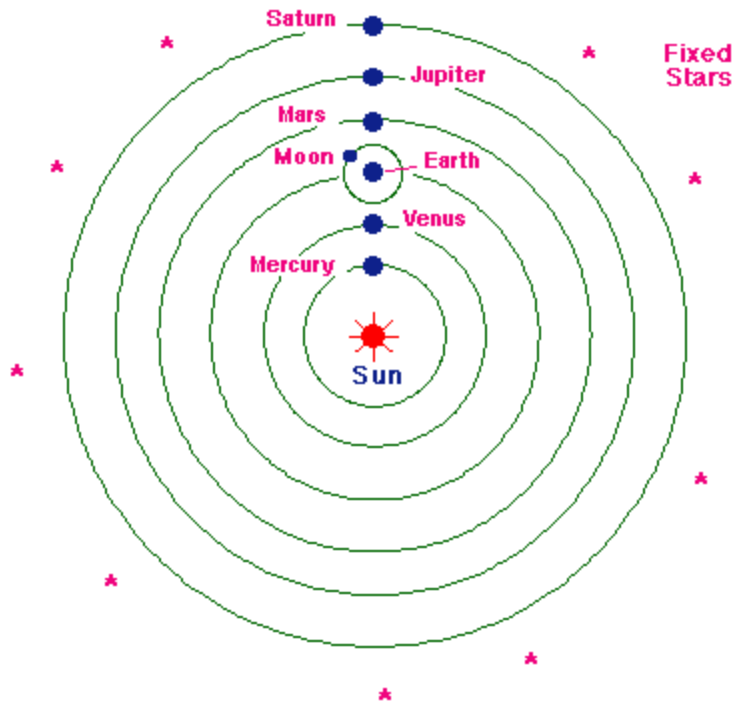
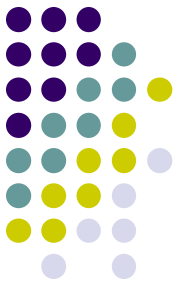
- Need for accurate navigation – precise prediction for astronomical events
- Printing press – wide spread of classical texts (Aristotle, Ptolemy) in authoritative editions
- Religious Reformation – fragmentation of Church, temporary softening of official Catholicism

Nicholas Copernicus (1473-1543)

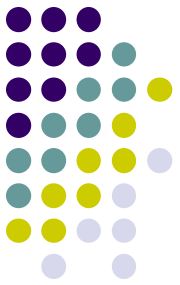


(Latinized of Polish Mikolai Kopernik). He is credited with introducing the modern heliocentric model. We do not know what was his reasoning. Perhaps, he just wanted to light the world from the center!

Copernicus's heliocentric model



Limitations



- Assumed that planets go on circles around the Sun. In order to fit observations, he had to include equants and epicycles.
- *Parallax* was a sticking point. Copernicus had to move stars further away.

Parallax

- Ptolemy:

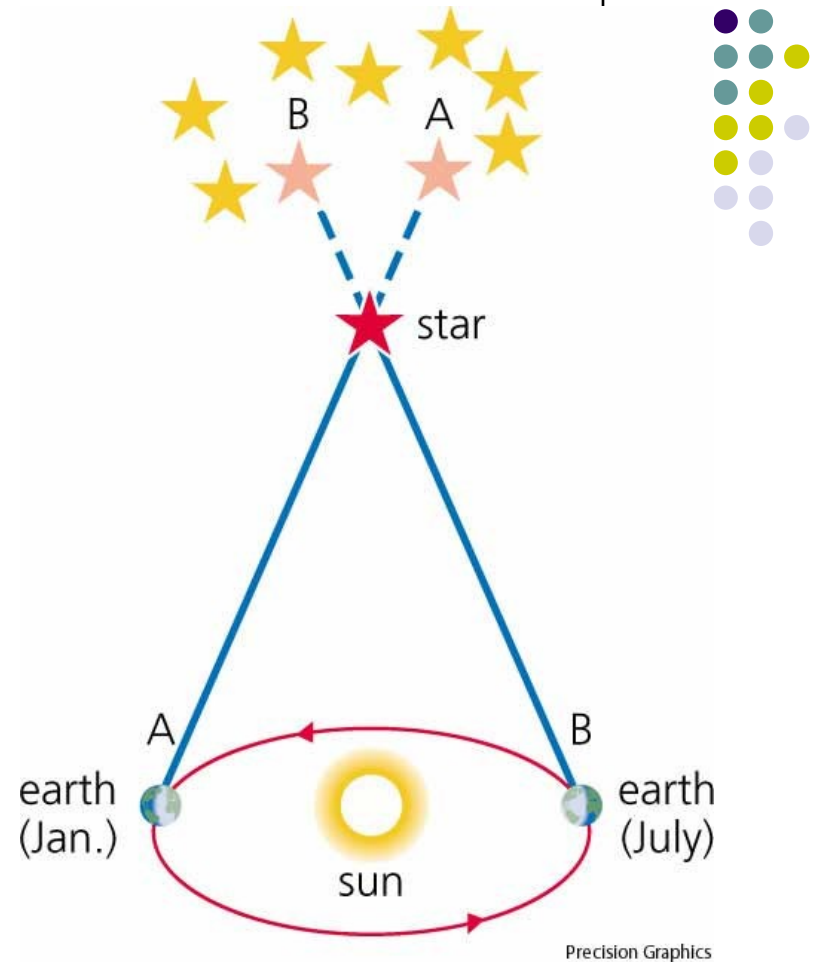
$$D_* = 20,000 R_{\oplus}$$

- Copernicus:

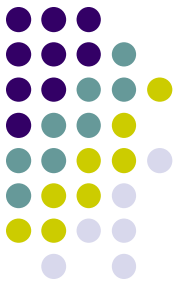
$$\begin{aligned} D_* &= 1,500,000 R_{\oplus} \\ &= 1.5 \times 10^6 R_{\oplus} \end{aligned}$$

- Reality:

$$D_* > 6 \times 10^9 R_{\oplus}$$



Big success



- Natural explanation for the retrograde motion of planets.
- Predictive power: a new planet should rotate slower than existing ones.

Tycho Brahe (1546-1601)



- He was a famous scientist and a heavy drinker (from which he might have finally died), which means that the two are not mutually exclusive.
- He repeated his measurements, i.e. made sure that his results are *reproducible*. Estimated the **errors** of his measurements; no one did it before him!



Remember, Aristarchus calculated that

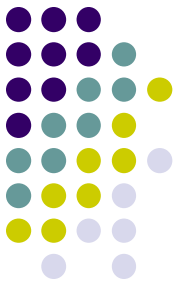
$$R_{\oplus} \approx 3 \times R_{\text{m}}.$$

Tycho Brahe would write this as

$$R_{\oplus} = (3 \pm 1) \times R_{\text{m}}.$$

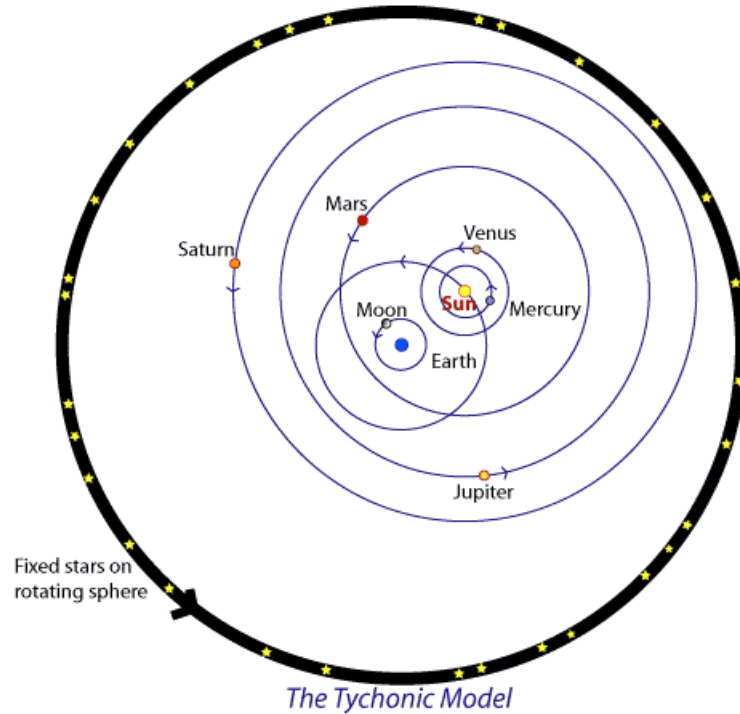
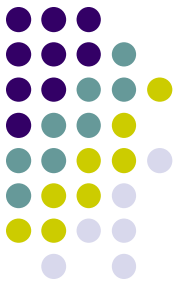
A modern value

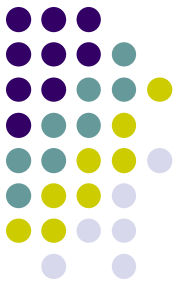
$$R_{\oplus} = (3.672 \pm 0.001) \times R_{\text{m}}.$$



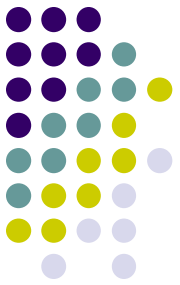
- Brahe was convinced that
 - Ptolemy model was wrong, since it did not fit observations.
 - Copernicus model was wrong, since he could not detect the parallax.

Tycho Brahe's cosmological model





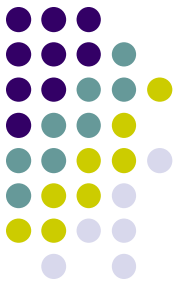
- If parallax is not observed, it could only be because of two reasons:
 - stars are too far away.
 - the Earth does not move.
- Brahe believed the stars were near because he detected their size (this however was an optical illusion). Thus, he concluded that the Earth does not move. This is a perfect example of correct scientific reasoning that leads to an incorrect conclusion.



His Successes

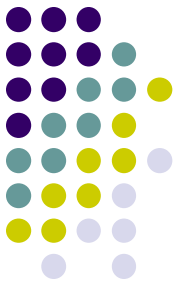
- In 1572 Brahe observed a “new” star, i.e. he saw a star where no star was before. Now we know that it was a *supernova*. This proved that the heavens were not immutable, eternally unchangeable. This was like a revelation to many people!
- (The next one occurred in 1604, and then another one in 1680. After that one, none happened in the Milky Way until the present day - so we are long overdue for a supernova explosion!)

His Successes II



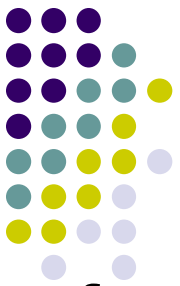
- He also triangulated an (currently unknown) comet in 1577 and proved that it flew beyond the orbit of Moon. Thus, it flew through the celestial spheres, which therefore cannot be solid and impenetrable (as Aristotle believed). That meant that the Earthly and celestial realms were not distinct, but might obey the same laws and be made of the same substances.

Johannes Kepler (1571-1630)



- He was an assistant to Tycho Brahe and inherited all his observational data.
- He lived in unfortunate times. He died in total poverty.





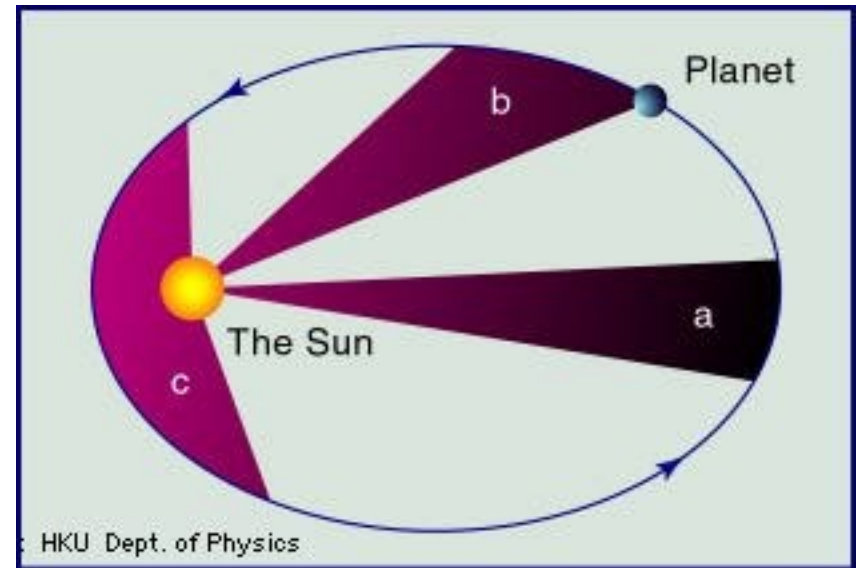
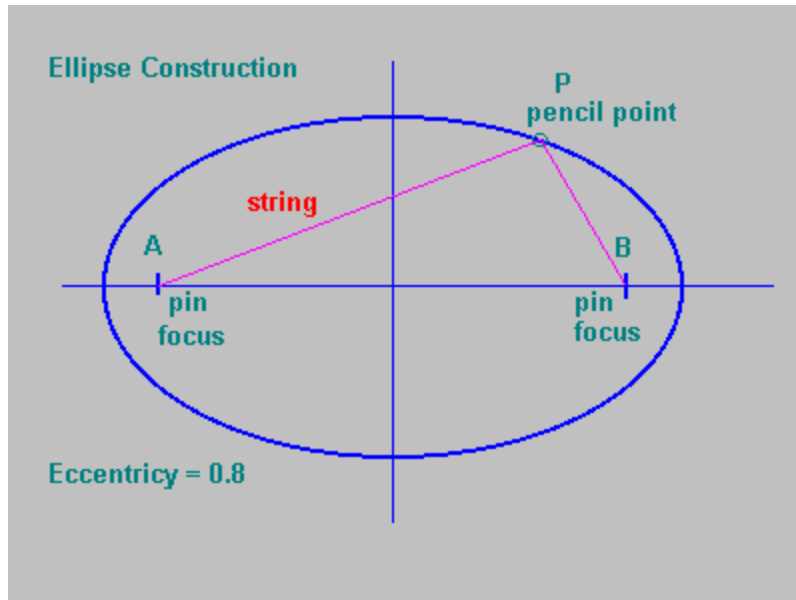
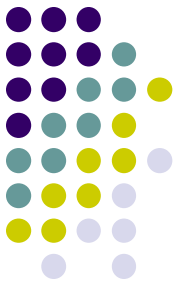
- He was faced with a serious problem: none of then existing models could fit the observational data to within Tycho's stated errors. He believed that Tycho calculated his errors correctly, so he embarked on developing a world model that was in agreement with observations.
- And then he had an inspiration!.. Not a circle but an **ellipse**. A single ellipse with the Sun in its focus was able to fit all the data, instead of equants and epicycles in the Ptolemaic model.

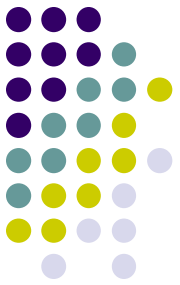
Kepler's Laws of Planetary Motion



- Planets orbit the Sun in an ellipse, with the Sun at one focus.
- The line from the Sun to the planet sweeps out an equal area in an equal time. Thus, planets move faster when they are nearer the Sun.
- The square of the period of the orbit is equal to the cube of the semimajor axis of the ellipse.

Kepler's first (left) and second (right) law

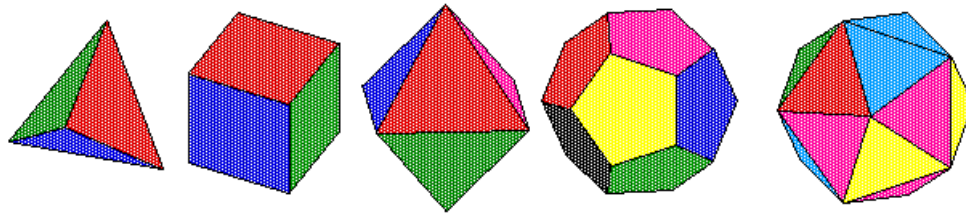




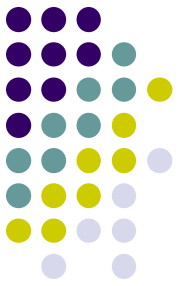
Kepler's third law

$$P^2 = R^3.$$

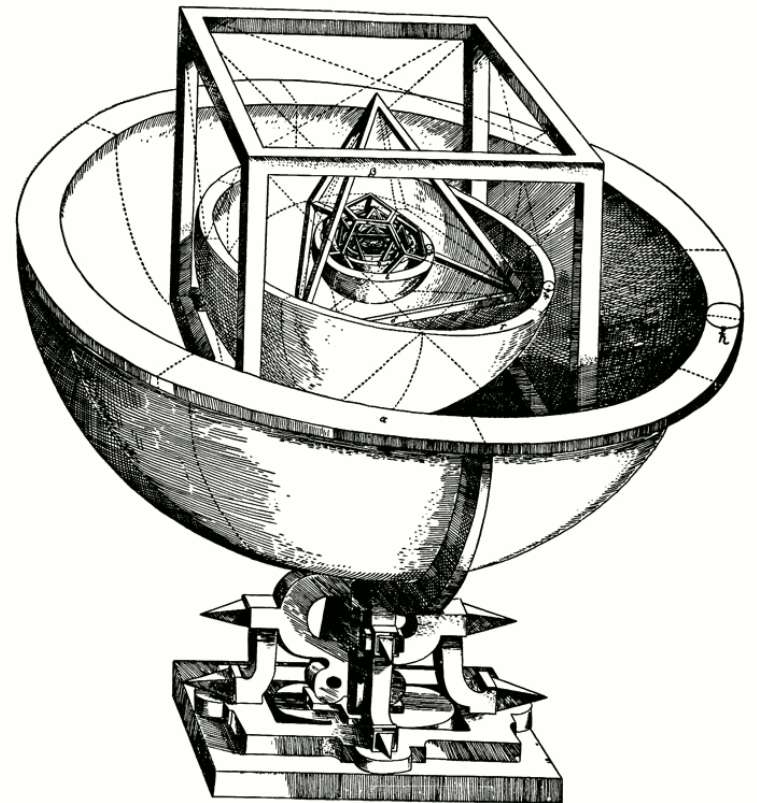
Very important note: *This is only true if the period P is measured in years, and the semimajor axis R is measured in astronomical units. One astronomical unit is equal to the length of the semimajor axis of the Earth orbit.*

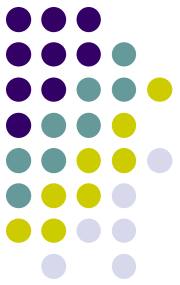


The Tetrahedron The Cube The Octahedron The Dodecahedron The Icosahedron



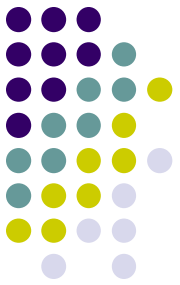
- *Despite all his great discoveries, Kepler was very prejudiced in his world view.*
- *He thought to relate the 5 distances between 6 known planets to 5 existing perfect (Platonic) solids.*





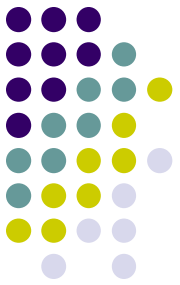
Kepler's Idiosyncrazies

- Measured distances between planets did not quite fit, but he found that he could relate them to (small) musical intervals.
- He thought that if the distances between planets matched exactly the ratio of Platonic solids, the world would be too dull.



Kepler's Idiosyncrazies

- He computed densities of planets and found them to correspond to different minerals:
 - Saturn: 0.324 (hardest gems)
 - Jupiter: 0.438 (lodestone)
 - Mars: 0.810 (iron)
 - Earth: 1.000 (silver)
 - Venus: 1.175 (lead)
 - Mercury: 1.605 (mercury)
 - Sun: 1.838 (gold)



Kepler's Idiosyncrazies

- Kepler believed that on a Day of Creation all planets must have been aligned in a grand pattern (God would not start with a mess!).
- He spent years computing positions of planets at around 4000 BC, adjusting his numbers to make them align. He failed.